TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

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No. 127

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THE AIR PROPELLER, ITS STRENGTH AND CORRECT SHAPE.

By H. Dietsius.

From Technische Berichte, Volume III, Part 2.

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February, 1923.

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By H. Dietsius.

Airplanes and airships, at the present day, often have en-
gine installations totalling several hundred horsepower, the
output from which must be transformed into thrust through the
medium of one or more propellers; so that, not infrequently, a
single propeller must transmit from 250 to 500 HP. The periph-
eral speed of the propeller blades, in such cases, often exceeds
200 meters (656 feet) per second and the load due to centrifugal
force may then amount to several tons. It is extremely desirable,
therefore, that the strength of propellers should be calculated
and not determined entirely by the workmen who are employed in
their manufacture.

The peculiarities of the propeller blade, the wide varia-
tions in the shape of its cross sections and its size, do not
allow of such preliminary calculations as may be made in a lat-
tice girder, but only of the subsequent verification of its
strength; particularly as the shape and dimensions of the propel-
ler must always be determined from aerodynamical considerations,
i.e., the diameter, the pitch, and the width of blade will depend
upon the power which is to be transmitted at a given R.P.M., with
the maximum anticipated efficiency.

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* From Technische Berichte, Volume III, Part 2.

The basis of the calculations is the condition which exists either when the propeller is on the testing stand, or when the airplane is at rest upon the ground, since the thrust then produced is at a maximum. The axial thrust while the airplane is in flight is not used since it decreases with the increasing airspeed. In a propeller running at N R.P.M. the following forces and moments are produced:

1    The centrifugal force for one blade $F = \omega^2 \int dm\, r$

where (see Fig. 1) dm is the mass, in mass-kgs, of a narrow section of the blade contained between two parallel planes cutting the blade at a distance r, in meters, from the axis of rotation and $\omega = \dfrac{\pi N}{30}$ is the angular velocity in meters per second.

2    The axial thrust produced, T, which can be measured on the testing stand, or calculated with sufficient accuracy, using existing data, from the expression $\dfrac{T}{P} = \dfrac{\text{thrust in kgs}}{\text{HP absorbed}}$ for a given diameter and horsepower.

3    The torque, $M = \dfrac{75}{2\pi}\dfrac{P}{N}60$ in m/kgs, acting in the plane of revolution of the propeller, and distributed between the two (or four) blades.

In order, however, to completely investigate all the stresses which are set up in the propeller, we must start with the elementary condition that the blade, as it moves through the air, meets with the resultant R of which the direction at least is approximately known, (See Fig. 2).

As in a supporting wing, this force is somewhat inclined to the rear and may be resolved into the two components  lift and drag,  which, by summation over the entire blade produce the propeller thrust  T  and the torque  Q,  respectively, the latter setting up an equal and opposite turning moment to the engine torque.

It is known that the center of pressure, at small angles of attack, lies in advance of the first third of the wing section.  T  deflects the blade in the axial plane  x - x,  while  Q  acts in a perpendicular direction thereto.  Besides this, the resultant force,  R,  imposes on the blade a torque in the direction of the arrow.  There remains for consideration, the influence of the centrifugal force  F.  If the blade were a straight rod, tension only could be induced in it by the centrifugal force; since, however, this is not the case, bending stresses also will be introduced.

In order to obtain tangible results, tests were carried out on a propeller 4.9 m (16 ft) in diameter, absorbing on the testing stand 500 HP at  N = 730 R.P.M. (See Fig. 3).  The integral in the expression  $F = \omega^2 \int_0^R dm\, r$  is best determined graphically.  The blade cross-sections  S  are measured by planimeter, and plotted on the  S-curve (Fig. 4).  From this a curve of

$$m\, r\, \omega^2 = Sd\, r\, \omega^2 \times \frac{\gamma}{g}$$

is obtained, making the assumption that  $\frac{\gamma}{g} = \frac{0.7}{9.81} \sim 0.7$  where  $\gamma$  is the specific gravity of the wood (walnut or ash).  The area of this curve then gives, to the appropriate scale, the total centrifu-

gal force $F$ acting on section $0$ (at the boss). The correspond-ing centrifugal force for another section, say No. 5 $F_5$, is formed by measuring the area enclosed by the $m r \omega^2$ curve between the blade tip and the given section. Thus we obtain in this manner the curve for the integrals $F = \int_0^R dm\, r\, \omega^2$. The true tensile stress on any blade section $S$ is then $k_f = \frac{F}{S}$. These values determined and plotted for all sections, give the curve $k_f = \frac{F}{S}$. It will be seen that $k_f$ is greatest for section 3, being approx-imately 100 kg/cm² (1422 lbs/sq. in), i.e. still a permissible value.

In order to obtain the thrust figures, the total thrust of the propeller must first be estimated, e.g., $T = 1500$ kg (3307 lbs), corresponding to a/high value of $\frac{T}{P} = 1500 : 500 = 3$. On one blade, the force is $\frac{T}{2} = 750$ kg (1653 lbs). The force $T$ is a component of $R$ (Fig. 2). This increases as the square of the speed $v$ with which the section under consideration moves through the air, thus $R = Csv^2$ where $s$ is a narrow section of the blade. As $v = r \cdot \omega$, $R = Csr^2\omega^2$ and as $T$ is a component of $R$, $T = C'sr^2\omega^2$ and $\omega$ being constant, $T = C''sr^2$. Assuming, at first, that $s$ does not vary with the radius $r$, that is, that the section is constant throughout, then $T$ is proportional to $r^2$. The variations of $T$ become thus extremely simple to plot (See Fig. 5). The square of each radius is plotted to some convenient scale, and thus a curve of $T$ values, whose scale is still to be deter-mined, is obtained. Corresponding to the decrease in blade sec-tion towards the tip, the area of the $T$ curve is rounded off. It can likewise be assumed that no appreciable thrust exists at sec-

tion 3. The shaded area should therefore correspond very closely with the pressure distribution. By integration of the area by means of the planimeter, an $\Sigma T$ curve is obtained, the ordinates of which, $\Sigma T_s$, give the thrust acting on the blade between s and the tip. Centrifugal force $F$ and axial thrust $T$ act simultaneously on the blade, as also does the torque $Q$, the latter being neglected for the moment. In section 5, Fig. 6, for example, $F_5$ acts radially, and $T_5$ is perpendicular thereto, or axially. Both forces produce the resultant $R_5$. The portion 4 - 5 will therefore tend to lie in the direction indicated by $R_5$. If these resultants $R$ are plotted for all the sections 0 - 9, and their directions plotted consecutively from 0, a contour k-k (Fig. 4) is obtained, forming, as it were, the ideal shape for the propeller; if the propeller was so shaped, bringing the center of gravity of the sections coincident with the curve $k - k$ then the forces $R$ will produce no bending stresses, and tension only will exist in the blade. The only care necessary is to ensure that the centers of gravity of the blade sections do actually lie on this curve, i.e. that the line of c.g's coincides with the curve, adjusting the sections accordingly (See Fig. 3). As $T$ in comparison with $R$ is very small, in our example 730 kgs $\div$ 30,000 kgs, the $F$ curve can be employed for the calculation of $k_f$ values without difficulty.

The calculation of the forces acting in the plane of rotation is made in an exactly similar manner to that of the thrust forces. The component forces $Q$, (Fig. 2) also vary as $r^2$, so that the

area of the thrust curve $T$, using a different scale, can serve also as the area of the curve representing the force $Q$. The c.g. of this curve is the center of pressure as shown in Fig. 5. From $M = Q\rho$ we can calculate $Q$, whose value equals that of the area of the curve, thus giving the corresponding scale. By the integration of the curve, a $\Sigma Q$ curve may be determined, and by combination with the $F$ curve, a new contour $k' - k'$ which represents the ideal curve of c.g. in the plane of rotation, may also be obtained. This line does not show such a considerable curvature as that produced by the $T$ forces, the forces $Q$ amounting in magnitude to only about 1/10 of the $T$ values.

If the propeller blade is given such a shape that the actual curves of c.g. in the plane of rotation and in the plane perpendicular to the same, coincide exactly with those calculated, the sections will be free from all bending stresses; this, however, is only true so long as the assumed condition of running obtains, namely, that the propeller is mounted on the testing stand, or that the airplane is stationary. With increasing forward translational speed, the R.P.M. increasing and the axial thrust decreasing, the curves giving the positions of c.g. will be elongated or extended, causing the propeller to bend. If this is to be avoided, the assumed condition must be modified by making the average speed the basis of the above calculations.

As a matter of fact, it would also be desirable to estimate the bending stresses in the blade, when it varies from the ideal shape; but the calculations required are, however, extremely in-

volved, the moments of inertia of the blade sections are not read-
ily ascertained, and the elasticity of the glued wood is fundamen-
tally subject to variation; while the correct shape of the blade
renders the bending stresses extremely small. It has, however,
proved possible to measure the deflection of a propeller in
flight, by means of electrical devices. In one case, the blade
tip, when running at the designed R.P.M. was found to bend for-
ward a distance of 80 mm (3.15 in). In another propeller (SSW.D.
No.108) of 4.90 m (16 ft) diameter, a movement of only 30 mm
(1.18 in) was observed. It will be acknowledged, however, that
a deflection of 80 mm (3.15 in) can prove dangerous and in any
event must have some influence on the steadiness of the running
of the engine. It has also been observed that those propellers
which show variations from the ideal shape have broken when being
swung for, starting. The deflection in the latter above mentioned
propeller, for the sections shown in Fig. 7, at points near the
leading and trailing edges of the blade, was measured with greater
accuracy. For this purpose, copper wires $\frac{1}{2}$ mm (.02 in) thick,
were inserted in the leading and trailing edges (Fig. 8) and con-
nected with the steel boss at one end and terminating in the wood
at the other. At the desired measuring points the wires were fil-
ed bright in order to assist sparking at those points. From Fig.
7 it will be seen that the deflection varies on the leading and
trailing edges, and that the blade has thus been twisted in such
a direction as to increase the pitch - the alteration being shown
in Fig. 9. It is not difficult to see why the torsion should

have produced this result, as the forces R, (Fig. 2), act nearer the leading edge of the blade, at some distance in front of the center of gravity of the section.

In order to ascertain what axial stress would be necessary in order to deflect this propeller 30 mm (1.18 in) at the tip of the blade, the propeller was rigidly supported at the boss, and loaded on the section at the radius 1.5 m (4.92 ft) from the axis, where it was found necessary to apply 40 kg (88.2 lbs) in order to obtain a deflection of 30 mm (1.18 in). As it was desired that the blade should not be injured, the load could not be greatly increased; but it may be assumed that the blade would have broken under a load of from 50 to 60 kg (110 to 132 lbs). In reality, however, the axial thrust in practice, amounts approximately to 200 kgs (441 lbs), which force, evenly distributed over the entire blade, would undoubtedly break it, but for the action of centrifugal force, which, by placing the blade in tension, diminishes the deflection.

Subsequent torque calculations on the lenticular-shaped sections of the blade, only allow of an approximate calculation of the moment of resistance, and the point of application of R also varies greatly, according to the angle of attack. Such approximate calculations have, however, shown that the torsional stress is very insignificant; but it should be observed that comparatively small forces can produce elastic deformation, and if periodically applied, may result in an objectionable "flutter" or "whip" of the blade.

In conclusion, an instructive incident may be mentioned which confirms the theory of the ideal curve of c.g.

When revolving a built-up propeller, composed of steel ribs and aluminium surfaces, a loud noisewas heard and upon interrupting the experiment, a break in the aluminium blade was discovered, at b, (Fig. 10), which extended almost to the steel rib, spreading to several millimeters in width at the edge. The propeller however, ran for some time in this condition, without the upper part of the blade being completely torn off, although the cross-section had been considerably reduced. As was seen later, the end of the c.g. line of the propeller was too far to the rear. After breaking at b the blade assumed a more favorable shape, the bending stresses were greatly diminished, and the cross-section at b, although weakened, was able to withstand the remaining stresses.

Summary:- It is possible to give a propeller such a shape that, under given conditions, viz., a definite speed of revolution and flying speed, the bending stresses in the blades will assume quite an insignificant magnitude.

Translated by the National Advisory Committee for Aeronautics.
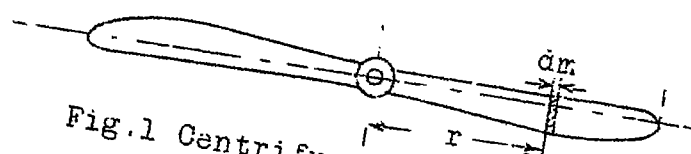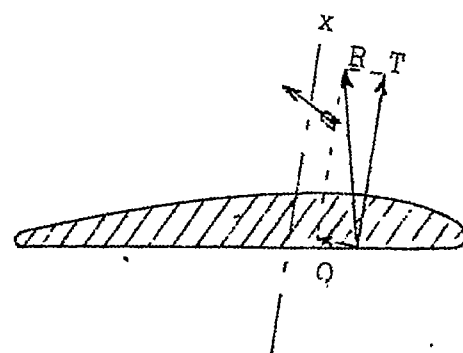
Fig.1 Centrifugal stresses in a propeller



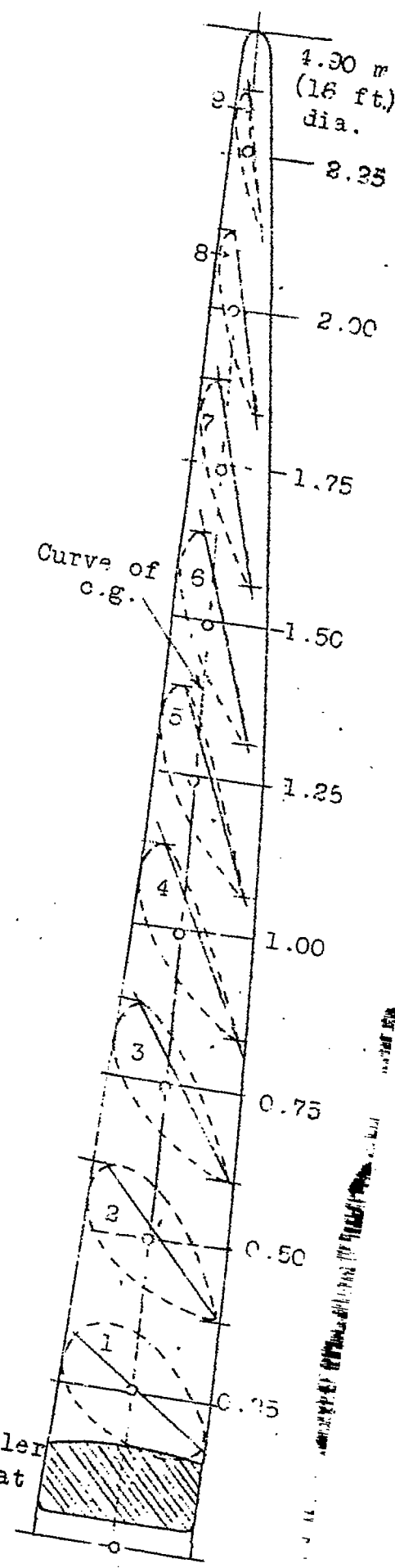Fig.2 Air forces on a propeller blade



4.90 m
(16 ft.)
dia.

2.25

2.00

1.75

Curve of
c.g.

1.50

1.25

1.00

0.75

0.50
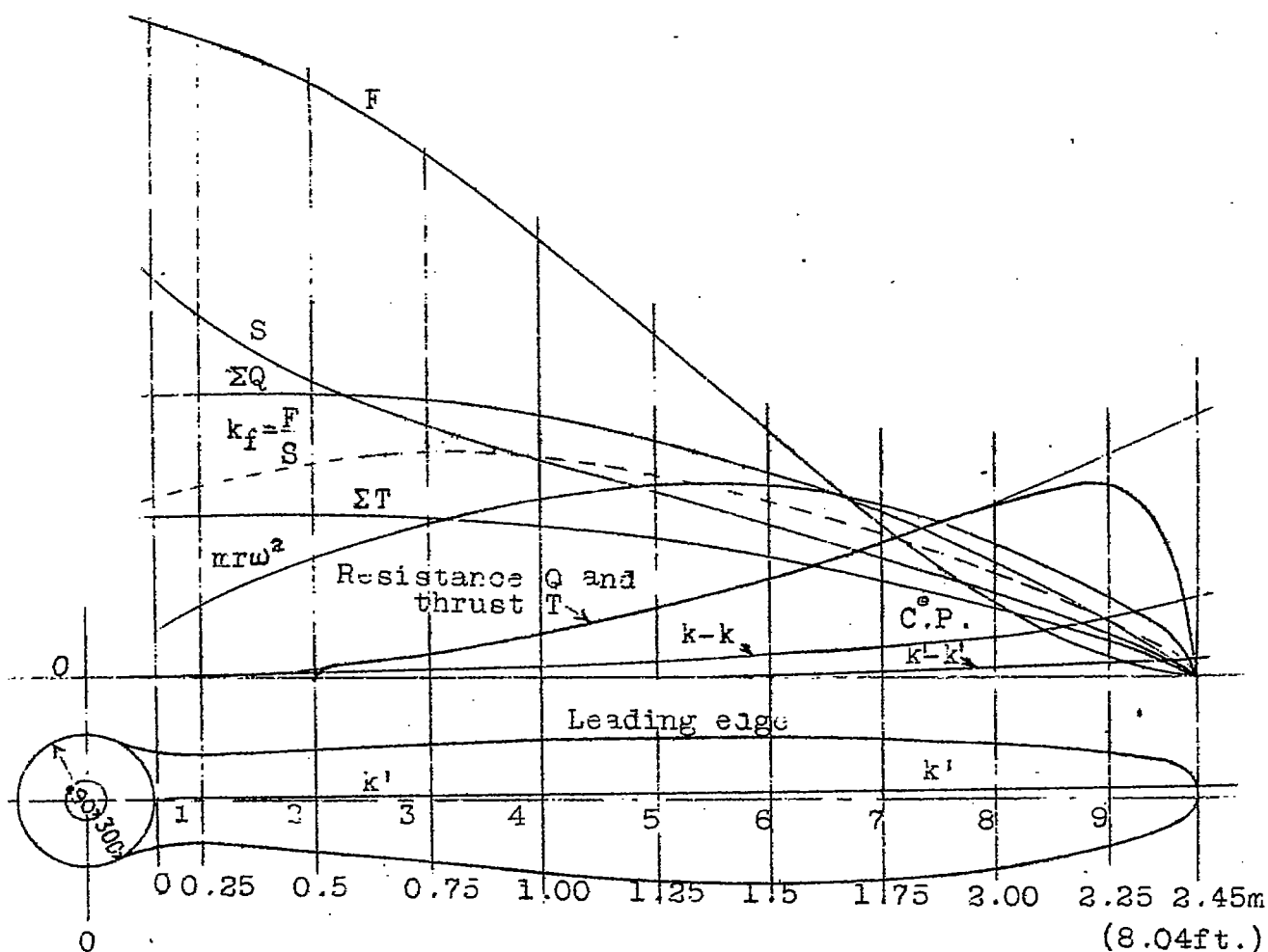
0.25

Fig.3 Propeller
for 500 HP. at
730 R.P.M.

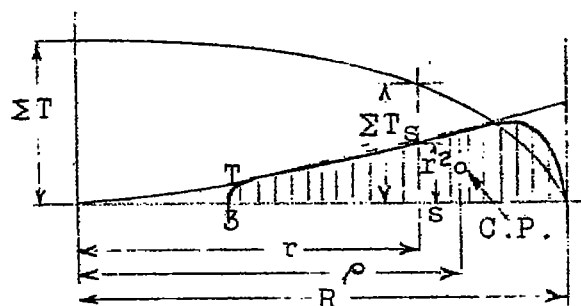Fig.4 Curves for the 500 HP. propeller at 730 R.P.M.



Fig.5 Curves for the deter-
mination of thrust


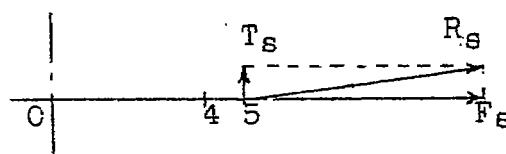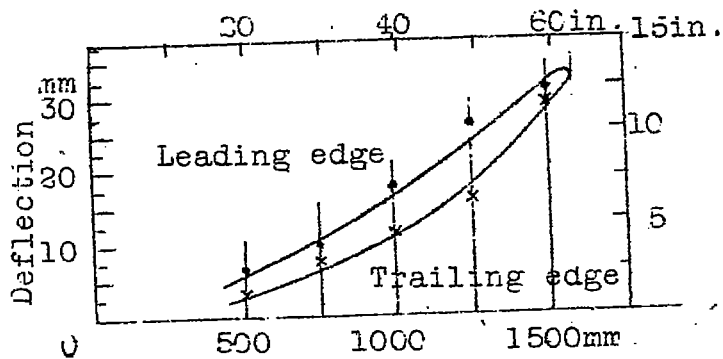
Fig.6 Resolution of cen-
trifugal force and axial
thrust

Fig.7   Curve showing deflection of
the SS W.D. No.108 propeller
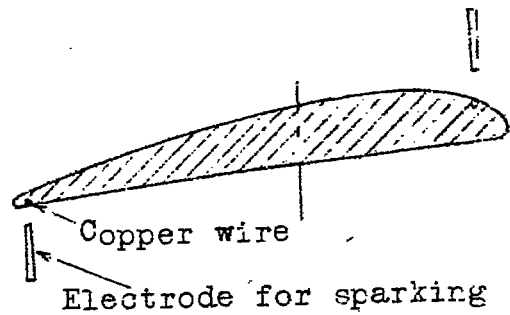at 925 R.P.M.



Copper wire

Electrode for sparking

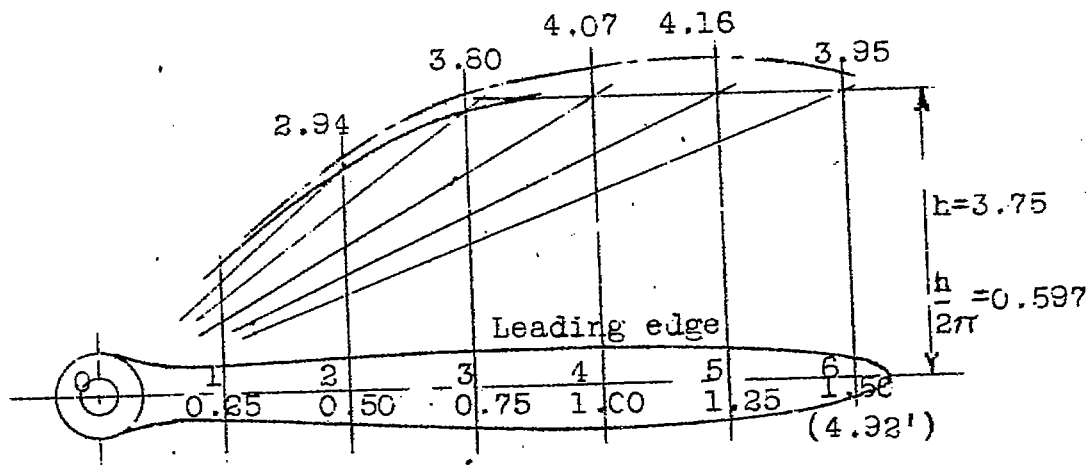Fig.8   Device for measuring
the deflection of a
propeller



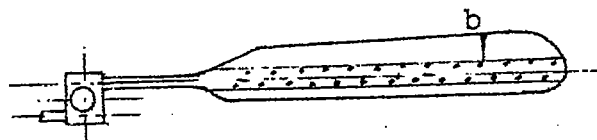Fig.9 Alteration in pitch of the SS W.D. No.108 propeller
due to deflection at 925 R.P.M.



Fig.10   Break in the aluminum
blade of a propeller